22269

Directorate of
Intelligence

~~Secret~~

Soviet Work on Radar Cross Section Reduction Applicable to a Future Stealth Program

An Intelligence Assessment

The author of this paper is , Office of Scientific and Weapons Research. Comments and queries are welcome and may be directed to , OSWR.

~~Secret~~
SW 84-10015
February 1984

Warning Notice	Intelligence Sources or Methods Involved (WNINTEL)
National Security Information	Unauthorized Disclosure Subject to Criminal Sanctions

Dissemination Control Abbreviations	NOFORN (NF)	Not releasable to foreign nationals
	NOCONTRACT (NC)	Not releasable to contractors or contractor/consultants
	PROPIN (PR)	Caution—proprietary information involved
	ORCON (OC)	Dissemination and extraction of information controlled by originator
	REL	This information has been authorized for release to...
	FGI	Foreign government information
	WN	WNINTEL—Intelligence sources or methods involved
	A microfiche copy of this document is available from OCR/DLB (351-7177); printed copies from CPAS/IMC (351-5203). Regular receipt of DDI reports in either microfiche or printed form can also be arranged through CPAS/IMC.	Classified b Declassify: OADR Derived from multiple sources
	All material on this page is Unclassified.	

Soviet Work on Radar Cross Section Reduction Applicable to a Future Stealth Program

Key Judgments

Information available as of 1 November 1983 was used in this report.

We feel certain that the Soviets did not have a Stealth program in the 1970s—a program that uses both body shaping and radar-absorptive materials to attain a true low-observable aircraft or any other platform. Because of the obvious high US interest in this area, the Soviets probably began an intensified research effort in the early 1980s which may have led to a developmental program now under way. Such a program could be well along before we become aware of it.

For the last 20 years the Soviets have used—with modest success—radar-absorptive materials or paint on submarines, reentry vehicles, aircraft, and possibly on spacecraft and ground vehicles. Their results are not comparable to the best US work, but the Soviet work has continued to improve in both quantity and quality. Given the attention to Stealth in the United States, Soviet application probably will become more widespread in the future. Most certainly, the Soviets will be highly motivated to assess US achievements in radar cross section reduction to improve their own position. An analysis of Soviets' open literature indicates that their understanding of the theory of radar cross section reduction is comparable to that in the United States.

A number of Western countries also have begun programs to reduce aircraft radar cross sections. As the technology becomes more widespread, technology transfer to the Soviets could begin to play a significant role in enhancing their work. [ ]

The Soviets probably will deploy in this decade some retrofitted aircraft and cruise missiles whose radar cross sections in the forward sector will have been reduced by a factor of 10. Such programs would primarily involve the application of radar-absorptive materials to existing platforms. The cross sections of bombers could be reduced in this manner to about 1 square meter; those of fighter aircraft could be reduced to a fraction of a square meter; and those of cruise missiles could be reduced to less than one-hundredth of a square meter. In some tactical engagements, such reductions would provide a significant advantage. Retrofitted aircraft or cruise missiles would be difficult to detect visually because there would be very little change in their external appearance

Radar cross section reduction [ ] may be possible by using body shaping in addition to radar-absorptive materials. We are not certain, however, if the Soviets can produce such aircraft or cruise missiles, particularly in large numbers. If they have such a program under way now, it is probably in the very early stages, and deployment probably would not occur until the 1990s because development of new systems requires about a decade.

Contents

Soviet Work on Radar Cross Section Reduction Applicable to a Future Stealth Program

Introduction

The radar cross section (RCS) of any object is a measure of how much energy it reflects when illuminated by a radar. The amount of energy reflected is determined by the size, shape, and material composition of the target, as well as the radar frequency, polarization, and direction of observation. The RCS value is usually expressed in units of area (square meters) or its equivalent in decibels per square meters (dBsm). This concept is applicable to most platforms: aircraft, helicopters, missiles, reentry vehicles, satellites, ships, remotely piloted vehicles, tanks, and trucks. Ships may have RCS values of approximately 10,000 square meters (40 dBsm), and aircraft range typically from 10 square meters (10 dBsm) to 1,000 square meters (30 dBsm). Cruise missile RCS values are considerably smaller—typically .01 square meter (−20 dBsm) to 10 square meters (10 dBsm)

RCS reductions by an order of magnitude or more often can be achieved over limited observation angles by retrofitting existing vehicles with radar-absorptive materials (see appendix). Greater improvements can be achieved with totally new designs which include body shaping as well as application of radar-absorptive materials. Such improvements require extensive research and development (R&D) efforts.

The smaller the RCS, the more difficult it is for the radar to detect the target. This is particularly true for low-altitude targets, because the radar must detect the relatively small target return in the presence of the much larger return from the ground clutter. In many current air defense situations, the radar return from the ground clutter greatly exceeds the return from the target, thus taxing to the limit the signal processing that rejects clutter. If the RCS of an aircraft or a missile is reduced sufficiently, the ordinary radar will be incapable of seeing it in the presence of the ground clutter.

In addition, reduced RCS in aircraft can allow the use of some electronic jamming techniques that would not be feasible with normal target returns. Self-protection jammers carried on bombers are limited by the maximum power they can emit. Because these jammers must compete with the strength of the radar energy reflected from the body of the aircraft, jammer power can be reduced if the aircraft RCS is reduced. Such jammers with realizable power levels can then mask the actual radar signal reflected from the body of the aircraft and spoof the radar by providing false position information

In both of these examples, aircraft survivability is increased.

Soviet Radar Cross Section Technology

Theoretical Base

Open literature has indicated that the Soviets have a thorough understanding of those aspects of electromagnetic theory that are required to analyze and predict RCS. Literature dealing with theory and mathematical concepts generally reflects original Soviet work, but literature dealing with applications of the concepts is primarily from Western sources. It is also apparent that there are more researchers in this field in the Soviet Union than in the United States. Some of the Soviet books examine in great detail very narrow topics almost academic in nature

The Soviet open literature contains hundreds of articles on electromagnetic theory applicable to analyzing and designing low RCS shapes although RCS reduction is rarely mentioned explicitly. The subjects discussed in the articles include waveguides, cones, cylinders, edges, gratings, lossy layers, impedance surfaces, anisotropic crystals, apertures in planar surfaces, and nonradiating modes in structures. At least some of the work probably was motivated by the desire to better understand and control the RCS of various platforms. The latest Soviet book on the Geometric Theory of Diffraction (GTD) presents all of the GTD theory in a coherent fashion in one publication. GTD is the theory describing how electromagnetic energy diffracts around edges and corners. This theory is one of the keys to understanding how much radar energy is reflected from complex objects such as aircraft.

The general Soviet understanding is also fostered through the All-Union Symposia, which are held regularly every few years. The Soviet theoretical work presented in these conferences is at least comparable in quality to the Western work in most areas.

In addition to doing good quality research of their own, the Soviets clearly study all US open literature. They reference the works of prominent US researchers in their publications, translate US professional journals, and attend US professional conferences. For example, in 1965 in the United States, a 1,138-page special issue on radar reflectivity was published at an unclassified level. Within one year, it was fully translated by the Soviets for their own use.

Measurement Capability

Although many advances have been made during the past 20 years in the theoretical approach to determining RCS values, measurements must still be made by all who work in the area to validate the analytic models. The Soviets published a book more than 10 years ago that indicated they understand the fundamentals of RCS measurements. The book reviews diffraction, modeling, various range configurations, parasitic scattering, measurement errors, and instrumentation—again borrowing heavily from US sources. To date, we have identified [redacted] three outdoor RCS measurement ranges [redacted] There are probably a number of indoor ranges [redacted] that would be suitable for making measurements of scale models.

[redacted]

[redacted] In the United States, targets to be measured are usually placed on columns whose RCS have been reduced to the minimum by shaping and treatment with radar-absorptive materials. At the time the [redacted] range was designed, the Soviets probably could achieve smaller returns from nonmetallic cables than from shaped columns. However, a very large outdoor suspension system, being unable to precisely control the azimuth of the targets, will limit Soviet diagnostic capability and, therefore, affect any efforts to achieve very low cross sections.

[redacted]

a second range, for measuring RCS of aerodynamic targets

[redacted]

[ ] The targets have included full-size fighter aircraft, surface-to-air missiles (SAMs), air-to-surface missiles, and drones, as well as scale models. [

]

[ ] We have also identified [ ] a third location for making RCS measurements [ ] [ ] was already in operation [ ]

[

] Measurements could be made at this test range at all frequencies—optical, infrared, and microwave—to determine the effectiveness of various paints and coatings. The facility also could be used to develop synthetic aperture radars in which high resolution is achieved through signal processing of observations taken from different angles.

Materials

Much of the Soviet work in composite materials is probably motivated by applications other than RCS reduction. Their strength, lightness, and rigidity make them suitable for many structural aerospace applications. However, when composites are combined into layers of thin absorptive sheets, the resultant structure can minimize the reflection of electromagnetic energy.

The Soviet program for composites involves thousands of scientists and engineers. [ ] data indicate that Soviet research work in fibers and metal matrices is probably comparable to that in the United States. Their fiber work has emphasized aramid, boron, and graphite fibers, but some work also has been done on carbon fibers. The Soviets have studied at least 60 different material combinations, with emphasis on composites based on aluminum, magnesium, titanium, copper, and nickel. Their technology base in composites probably is adequate to support the production of an all-composite aircraft in the 1990s. Such an aircraft, with proper shaping, has the potential of producing very low RCS.

The Soviets already have a good understanding of more conventional ferrite-based radar-absorbing materials as is evidenced by a recently published book on the subject. The knowledge expressed in an earlier book on elastic magnetic materials would be useful in developing flexible radar-absorptive materials for covering the platform structure.

Paint can also serve as the medium containing radar-absorptive material. The paint usually contains small ferrite particles which act as small magnets that tend to realign themselves with the oscillating electromagnetic field, thus absorbing the energy and converting it to heat. Soviet open literature indicates that the Soviets have the capability to prepare solid iron oxides (ferrites) and mix them into various polymeric resins, such as epoxys and plastics, to produce radar-absorbing paints. The thickness of the material will determine the frequency band at which absorption will be maximized. We do not believe that the Soviets have fielded ground force vehicles painted with radar-absorbing paint, but their technology is mature enough to support such applications in the late 1980s. They have applied radar-absorbing paint to aircraft in the past, but only with limited success. We are uncertain of the effectiveness of the Soviet paint.

Transfer of Technology

The United States is no longer the only Western country interested in reducing the RCS of aircraft. As similar work builds up in other countries, the technology will proliferate, making technology transfer to the Soviet Union more likely. Some examples [ ] [illegible] of grow[illegible] wide interest in radar-absorptive materials [illegible] applications follow:

- An anechoic chamber for making indoor RCS measurements, built in 1978 for the Avions Marcel Dassault-Breguet, France, is now being used to reduce the RCS of a Mirage-class fighter.

- Polish researchers at the Wroclaw Technical University have completed theoretical work in paint which absorbs electromagnetic waves and now are carrying out laboratory experiments [illegible] paints, [illegible] The effectiveness of this paint is unknown.

- Bulgarian researchers at the Univers[illegible] were measuring various radar-[illegible] in the early 1970s. This work was probably for the development of attenuators to be used in microwave circuitry.

[illegible] each of the [illegible] has [illegible] trial and error. [illegible] interest in [illegible]

[illegible] samples of [illegible] to be used in lining the [illegible]alls of their new anechoic chamber for [illegible] antenna measurements. [illegible]

- [illegible] of the [illegible] Physics, Moscow, sought information [illegible] on mate[illegible] modification to increase [illegible]

- [illegible] materials. The [illegible] in this effort is unknown.

- data indicate that to improve their capability in carbon/carbon composites, the Soviets have exploited Western literature and conferences, invited Western experts on lecture tours, and purchased hot isostatic presses from Sweden, France, and the United States.

- S. Ye. Salibekov noted at the 1972 All-Union Conference on Composite Materials that a review of US literature concerning fiber/matrix interactions in metal matrix composites had led to a Soviet program on applying nickel coatings on graphite fibers for graphite/aluminum composites.

Applications

While the Stealth publicity in the United States has been concerned with only aircraft, the technology and concepts can be applied to many different platforms. Indeed, the Soviets have attempted to reduce the RCS of several different kinds, although with only limited success to date

Submarines

The Soviets have been interested in the application of radar-absorptive materials to submarines for more than 20 years. Their work has included the following:

- the Krylov Central Scientific Research Institute of the Shipbuilding Industry was conducting research on radar-absorptive coatings for submarines in the early 1960s. The work was to determine the optimum combinations of rubber, epoxy, cotton-glass, and mica layers for electromagnetic and acoustic absorption.

Reentry Vehicles

The Soviets also have long been interested in reducing the RCS of reentry vehicles:

- In 1964 the Institute of Chemical Physics, Moscow, collaborated with Institute 108, Moscow, on the reduction of RV cross sections. The approach was to create artificial ionization in the upper ionosphere by throwing sodium out of the RV; the sodium was to react with the oxygen present in the ionosphere to create an ionized layer and, therefore, reduce the RCS. More likely, the project was designed for seeding the RV wake to reduce its overall RCS signature

[redacted]

Aircraft

There have been numerous reported examples during the past 20 years of Soviet attempts to apply radar-absorptive paint to aircraft, but we see no evidence of a continuing program or of deployment of large numbers of such aircraft. Similarly, there are indications of interest in the use of composites for RCS reduction but no evidence of deployment:

[redacted]

- [redacted]
- [redacted]

- Two F-14 flight crews intercepted two Soviet Bear aircraft in 1979 which were painted dark gray, had no visible identification numbers painted on the fuselage, and produced smaller-than-normal radar returns. The cause of the reduced radar returns remains uncertain.

[redacted]

The Soviet aircraft currently in development have no outward signs of RCS reduction, but we believe some of them will have features that will significantly reduce their RCS. This is true for the SU-27 [redacted] and MIG-29 [redacted] for example, which strongly resemble US aircraft of contemporary design such as the F-15 and F-16. The same applies to the latest Soviet bomber, the Blackjack, which seems to be a scaled-up version of the B-1. Another aircraft currently under development [redacted] is a high-altitude, long-endurance vehicle similar to the U-2. None of these aircraft exhibit any evidence of the ground-up configuration design necessary to achieve the minimum RCS. [redacted]

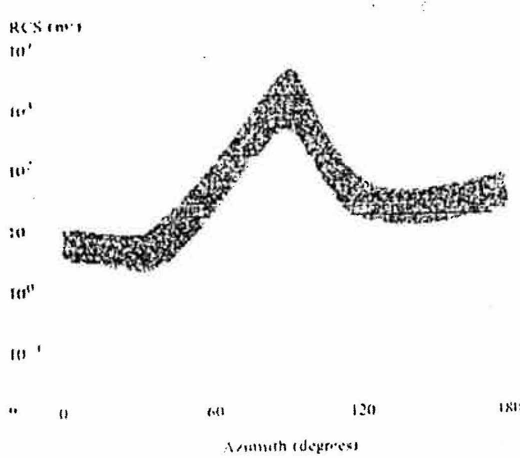
Although the Soviet RCS reduction technology is not comparable to the best US work, the quality and quantity of Soviet work over the past 20 years have been increasing. And some of the aircraft noted above now in testing probably will incorporate some techniques that would reduce the RCS value by an order of magnitude in the forward sector. These aircraft could include such features as conducting windshields to reflect the incident radar energy, engine inlets that are curved and/or lined with radar-absorbing material, conducting band-pass radomes, and canted and lined bulkheads. All of these techniques have been discussed in US open literature, and the Soviet understanding of materials and electromagnetics is adequate to support the implementation of such techniques. [redacted]

Such methods of reduction probably will be incorporated in some operational Soviet aircraft after the mid-1980s. Because it typically takes the Soviets about 10 years to develop a new aircraft, the bomber with the smallest RCS expected to be a threat to the United States in this decade probably will be a Blackjack. It may incorporate the RCS reduction features just mentioned. The figure shows the upper and lower bounds of our estimates of the reduced Blackjack RCS at X-band (8 to 10 GHz) frequencies. The actual smoothed value at any azimuth angle will probably be between these bounds. The values will increase as frequency decreases. For some azimuth angles the cross section of the bomber could be as little as 1 square meter. After a similar retrofitting, the cross section of a fighter aircraft could be a fraction of a square meter.

Radically new Soviet aerodynamic designs that would incorporate extensive use of radar-absorptive materials could be operational in the 1990s and have cross sections reduced by another order of magnitude. Whether the Soviets choose to develop new aircraft from the ground up to minimize the radar cross section and therefore incur aerodynamic penalties will depend on their perception of their requirements.

[redacted]

Reduced Blackjack Radar Cross Section, (8-10 GHz)



301638 2-84

[redacted]

Cruise Missiles

Reducing the cross sections of cruise missiles is one of the more attractive applications because of their inherently small size and relatively simple shape. The smallest Soviet cruise missiles, such as the SS-NX-21, for example, could probably be retrofitted to reduce the cross section from less than one-tenth to less than one-hundredth of a square meter in the forward sector and thus improve their survivability. Work probably is under way to reduce cross sections of cruise missiles, thus making them ready for deployment in this decade.

Ground Vehicles

An examination of [redacted] revealed little evidence of the Soviets' attempt to reduce RCS in ground vehicles. However, work is probably under way to measure the signature of ground vehicles [redacted] This Soviet activity could support widespread use of radar-absorbing paint before the end of the decade. We are uncertain of the paint's effectiveness, however, because it would depend upon the tactical situation, the vehicles, and the technical characteristics of sensors observing the vehicles.

Appendix

Low Radar Cross Section Technology: A Tutorial

This appendix [redacted] will focus on aerodynamic targets, but most of the principles of RCS reduction are general and could be applied to other targets as well.

RCS Reduction

The RCS of any radar target can be reduced passively in two basic ways: incorporate surface shapes which minimize the reflection back in the direction of the radar or utilize special materials to absorb the electromagnetic energy incident on the target. [redacted]

Body Shaping. The shaping approach can best be understood by considering the radar wavelength in relation to the target dimensions. The frequency of a typical fire-control radar is about 10 GHz, which produces wavelengths of about 3 centimeters. Most aircraft dimensions are much larger than this, and the reflection can be viewed as an optical phenomenon. Most of the incident energy will be reflected from the aircraft surfaces like a light beam, and the largest returns will come from surfaces that are perpendicular to the incident energy. This reflection is called specular. A cylinder will produce a specular return along its entire length when viewed from the side. A sphere will have a specular return from one spot, independent of its orientation. Some nonspecular reflection also occurs since the radar wavelength is actually not that of light, but this contribution is much smaller than specular reflection in most cases. Nonspecular reflection becomes a significant contributor to the total reflected power only after the specular returns have been eliminated. One way to reduce the amount of energy reflected back to the radar is to shape the surface so that the energy is reflected away from the radar. For example, if the nose of a missile is made pointed instead of round, the amount of energy reflected from it when seen from the front will be reduced considerably. Similarly, if the underside of an aircraft could be made perfectly flat, a ground-based radar looking up at the aircraft would see in effect only a very small RCS target, because most of the energy would be reflected away from it. In both examples, the incident energy has been redirected by the target shape in some direction away from the radar. For some targets, there may be aspect angles for which it is simply not feasible to redirect the energy. For example, when viewed from the side, the RCS of current-generation cruise missiles is very difficult to reduce.

The principal difficulty is that most shapes that minimize the radar return incur some aerodynamic penalties such as reduced stability, range, and maneuverability. The derivation of aircraft or missile designs, which minimizes the radar return while maintaining acceptable aerodynamic performance, is a new R&D area. Even more capable control systems will probably be needed to compensate for instabilities in low RCS designs. Baffle arrangements and mesh screens can be used to hide the engine intakes—a major contributor to the total reflection—from the radar while still allowing air to pass through; however, these techniques can cause a major reduction in engine power. Engine inlets can be curved, at the expense of reduced air flow, to reduce the radar reflections from the inlet inside walls and the engine. Inlets can also be recessed inside the fuselage to hide the opening from the radar. They can be placed above the wing to reduce the RCS signature when viewed from below and below the wing when viewed from above. Another technique is nonplanar inlet face shaping. To reduce the RCS of engine nozzles, several approaches are being considered: two-dimensional nozzles; high-aspect ratio nozzles; ejector nozzles; and nozzle/airframe integration, which will provide partial shielding of the opening

Before RCS reduction techniques can be integrated into practical aircraft designs, intensive analytical/semiempirical test studies will have to be performed by the Soviets to consider the interactive effects of different observable signatures, not only on each other but also on aerodynamics, propulsion, configuration, and structure. Viable trades can then be established during the vehicle design process. The promising aircraft configurations must then be comprehensively tested to validate preliminary data estimates, isolate and identify the RCS contributors, and refine the designs to further reduce the signature levels. Unprecedented cooperation between experts in aerodynamics and electromagnetics will be required, because much of the theoretical work has occurred in the academic arena. Further work will include the development of new computer codes, wind tunnel and RCS measurements, and extensive flight testing.

Absorbing Materials. The second principal way to reduce RCS is to utilize radar-absorbing material (RAM). Some of the materials which could be used in RAM are graphite fibers, graphite/epoxy composites, ferrites, Kevlar material, rubber, elastomers, and plastics. The materials can be in the form of inks, sheets, honeycombs, dielectric single-core sandwiches, multilayer cores, magnetic core laminates, and hybrid sandwiches. Magnetic powders in the form of flakes, microspheres, and chopped wire rod can be loaded into silicone rubber and/or epoxy. High dielectric constant and magnetic fillers can be added to polymide-based graphite/carbon resistive inks. The inks or coatings can then be placed on kapton film and glass/phenolic honeycomb. Some of these materials can be made readily in small quantities, but large-quantity production may require new technologies. Improved fabrication techniques and methods of bonding these materials to aircraft structures are also needed. Radar-absorptive materials can be applied to metal surfaces in those locations where the majority of the reflected signals are produced or they may be used as actual radar-absorbing structures (RAS). The use of absorbing composite materials for integral structural applications has the potential to improve strength-to-weight ratios in addition to reducing radar signatures. Much work is still required to verify the feasibility of manufacturing typical composite RAS aircraft or missile sections and to verify the predicted performance.

Engine inlets and exhaust nozzles of jet aircraft are large contributors to the total reflection when viewed from the front or from the rear, respectively. Sharp leading edges of the inlets act as linear radiators, and the inlet duct may act as a low-attenuation waveguide. The resulting standing waves and edge-diffracted fields can produce strong reflected fields. To date, many methods of inlet RCS reduction have resulted in only limited RCS reduction and/or significant performance loss. If RAM is applied to the engine cowling lips and the inside of the inlets, the electromagnetic energy will be absorbed as it is reflected inside the inlet, and the amount that is reflected back to the radar will be greatly attenuated. The principal difficulty with this approach is that most materials that are good absorbers of electromagnetic energy cannot withstand the very high temperatures of engine inlets or exhausts. The radar-absorbing materials presently available do not have the combination of mechanical and electrical properties required for integral structural design and high temperature applications. Encapsulation of temperature-sensitive magnetic particles in insulating binders is one approach to resolving this problem. Single-ramp, two-dimensional exhaust systems have significantly more potential for RCS reduction than round nozzles. An argument against the use of two-dimensional exhaust systems has been the increased weight of such systems, but current developments in carbon-carbon composite technology are expected to provide lighter weight structural materials

New microwave-absorbing materials, material combinations, and structural mechanical concepts must be developed for application to future military aircraft. Most RAM is either too heavy to apply over the entire aircraft or is effective only over a limited band of radar frequencies. Therefore, more R&D is needed to reduce the weight and increase the bandwidth of RAM for aircraft applications. Radar-absorptive paint (RAP), which can also be relatively heavy, could be applied to tanks without appreciably increasing the total weight. RAP would not be practical for most aircraft applications

Other, more specific techniques can reduce the RCS of aircraft. These techniques can be considered as special cases of the aforementioned generic body shaping and materials application approaches. Canopies and windshields, which are transparent at optical frequencies but which are reflective at microwave frequencies, can be used to reduce the radar reflection from the inside of the cockpit. For most aircraft, cockpits are a major contribution to the total reflected power because they contain many flat surfaces. Metallic radomes can be designed in principle which will be transparent at only one frequency, thus concealing the radar antenna from observation at all frequencies except its own. Most avionics antennas, particularly radar dishes, increase the aircraft RCS when viewed from the front. A simple expedient may be simply to cover the antenna bulkhead with absorbing material and to cant the radar antenna away from an observing threat radar. This may be a particularly effective approach for phased-array antennas

Sometimes RAM is incorporated in aircraft to improve avionics antenna performance, not to reduce the RCS of the aircraft. RAM in the bottom of an airborne interceptor radome will reduce the downward-looking antenna sidelobes, thus reducing the ground clutter and, therefore, improving the overall performance of the airborne intercept radar. Radar-absorptive materials could also be used around recessed airborne jammer antennas to improve their radiation pattern

RCS Calculations

The two principal ways of obtaining the RCS of a given target are to calculate it analytically or to measure the actual vehicle or a scale model of it.

Exact theoretical solutions for RCS have been developed for only a few simple shapes—spheres, ogives, and elipsoids. The usual approach to calculating the reflected radar power from a complex shape such as an aircraft is to first break it down to the basic shapes for which solutions exist, calculate the reflection from each of the simple shapes separately, and then properly add the results. Computer codes allow one to input entire complex bodies such as aircraft using three-view drawings into the computer, which then carries out the necessary calculations. One of the most widely used mathematical tools is the GTD. Diffraction coefficients are used to calculate how much of the incident radar energy is diffracted around edges, and analytic models of creeping and traveling waves are used to calculate how much energy propagates along the surfaces. In the theoretical area, much more work needs to be done to improve the modeling of cavities such as engine inlets, engine exhaust nozzles, and cockpits. Many of the computer codes producing the most accurate results also require inordinate run times, and more work is needed to improve their efficiency as well as accuracy. Of particular importance is the accuracy of modeling such radome appendages as strakes, Pitot tubes, and lightning protection schemes

If the radar wavelength becomes a significant fraction of the target body—as would be the case of a 150-megahertz (MHz) (2-meter wavelength) radar observing a cruise missile—optical methods, such as GTD, break down and other approaches must be used. One method is to model the target using a large number of conducting elements to outline the target, solve for the currents in the elements, and then calculate the net field reradiated by the currents. This approach is sometimes referred to as the Moment Method. One recent advance, which is showing considerable promise, is the modeling of complex surfaces using small, curved patches and calculating the field radiated by all of the patches. The analytically derived results may agree with actual values to better than 6 dB, that is, a factor of 4. Development of good analytic modeling tools that can predict the RCS values reliably is a key requirement to the development of new low RCS aerodynamic designs.

RCS Measurements

For high confidence, measurements are still needed, particularly for new aerodynamic shapes. Measurements can be static or dynamic; each has its advantages and disadvantages. In static measurements, the target is either supported on a pole having an RCS that has been minimized or suspended from some structure using nonmetallic lines. A calibrated radar is then used to measure the strength of the reflected energy as a function of the aspect angle, as the target is rotated. The reflections from the pole or the lines are reduced as much as possible to minimize the contributions to the reflection from the target itself. But some reflections from the target support always remain. Their presence would become particularly significant when measuring physically very large, but low RCS targets because a heavy support structure would be needed, and reflections from such structures can be significant. The pole mounting can provide very accurate position control.

Sometimes it is not practical to measure an actual aircraft because of its size, weight, or unavailability. In that case, a model reduced in size can be used instead, providing the wavelength of the calibrated instrumentation radar is reduced proportionately. Measurements using scale models have several limitations. Models often cannot reproduce accurately all of the RCS contributors of an actual aircraft such as cooling ports, avionics antennas, and hinged control surfaces. Also, it is not possible to measure accurately the effects of any RAM application since the material properties do not scale linearly with frequency.

In dynamic measurements, the vehicle to be measured is actually flown past a calibrated instrumentation radar. This method provides the most realistic data but only over limited aspect angles. It is also very expensive, and special inertial instrumentation aboard the aircraft may be necessary to provide accurate vehicle attitude information. This would be needed to relate the radar measurements to the angle at which the aircraft was observed

In most cases, radar calibration is accomplished by using a sphere of an appropriate size since this is one of the few objects whose RCS value is known exactly. The sphere may be placed on a pole, suspended from towers, elevated by a balloon, or dropped from an aircraft.

For increased security, the static tests could be performed outdoors at night or indoors in anechoic chambers. Dynamic tests could be performed in extremely remote locations or at night.

RCS Enhancement

Sometimes efforts are made to actually increase the RCS. This can be accomplished by adding Luneberg lenses or corner reflectors to the target. Both devices have the effect of focusing the reflected energy back in the direction of the radar, thus increasing the reflected energy and, therefore, the effective RCS. A typical RCS enhancement application would be to make the reflected signal from small, inexpensive target drones appear to be as large as from bomber aircraft in air defense exercises. Such drones also could be used to simulate aircraft in combat.